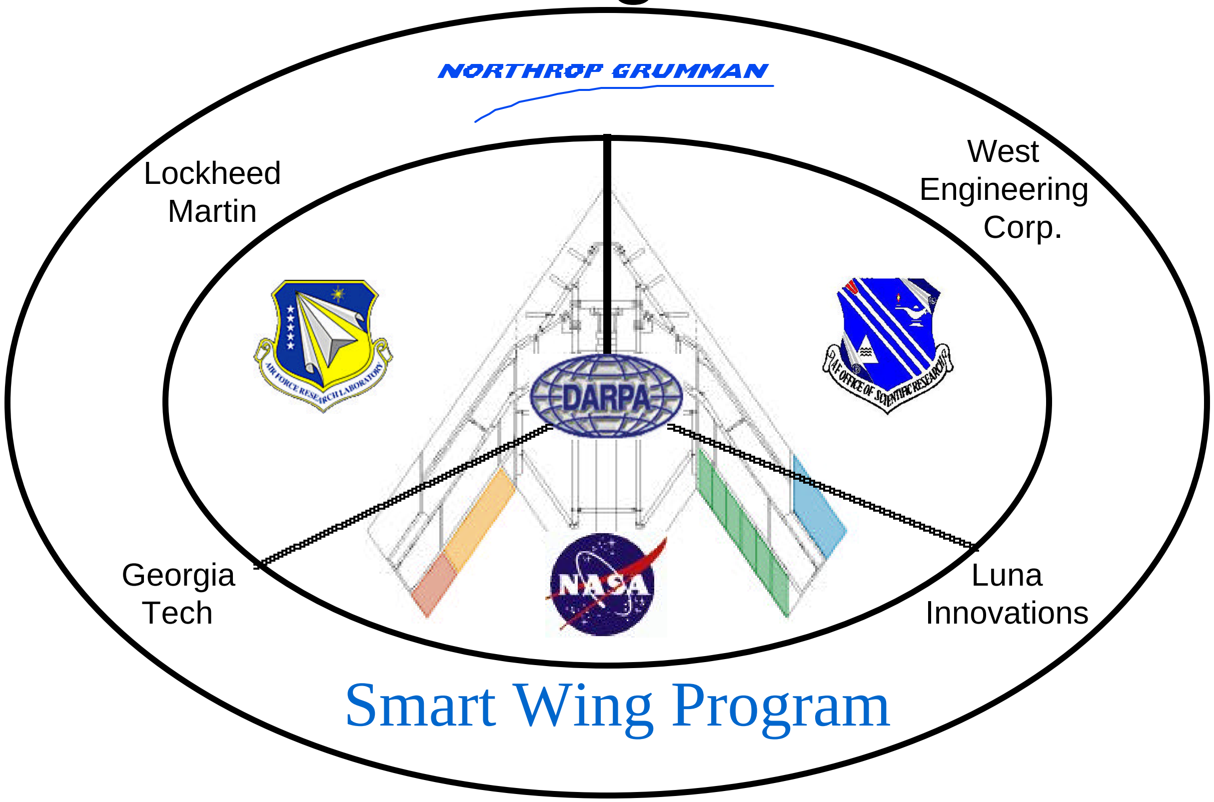
DARPA / AFRL / Northrop Grumman Smart Materials and Structures Demonstration

Smart Wing Phase 2



Dr. J. N. Kudva

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26 June, 2000

DARPA Technology Interchange Meeting

Agenda

- Program Overview
- Test 1 Summary
- Test 2 Preparations
- Summary Remarks
- SMA Actuated Control Surface Overview (B. Carpenter)

Acknowledgments

- Research Funded by DARPA
  - Contract Number F33615-C-97-3213
  - Dr. Ephraim Garcia - Program Manager - DARPA
  - Dr. Janet Sater (IDA)
- Contract Monitor - AFRL
  - Maj. Brian Sanders
- Wind Tunnel Facilities - NASA Langley TDT
  - Dr. Tom Noll - Anna McGowan - Jennie Florance - Seun Kahng
  - Renee Lake - Carol Wieseman - Tony Rivera - Tom Finley
  - Al Burner - Gary Fleming - John Hoppe
- Lockheed Martin - Denver
  - Bernie Carpenter - Jerry Draper - Kristi Mederos
- Luna Innovations
  - John Troll - Cliff Bell
- West Engineering Corp.
  - Mark West
- Universities
  - UCLA (G. Carman) - UTA (S. Joshi) - Georgia Tech (C. Lynch)

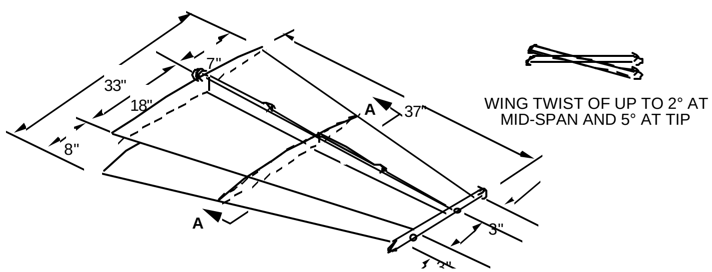
Program Overview

Program Objectives

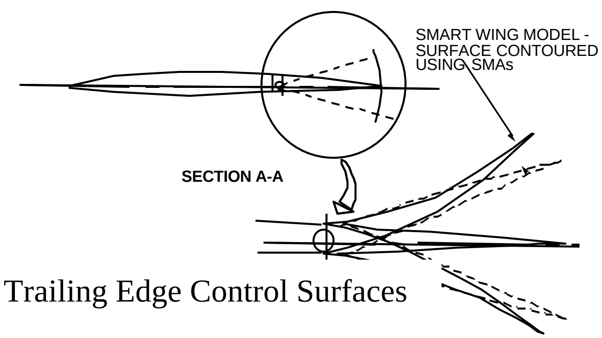
Demonstrate improvements in Aerodynamic (L/D, Maneuver and Aeroelastic) Performance of Military Aircraft using Smart Materials and Structures Based Actuation Systems:

- Design, Fabricate and Test Scaled Semi-span and Full-Span Models
- Address System Integration Issues
- Lay the Ground Work for Technology Transition Via a Flight Test in a Potential Follow-on Program

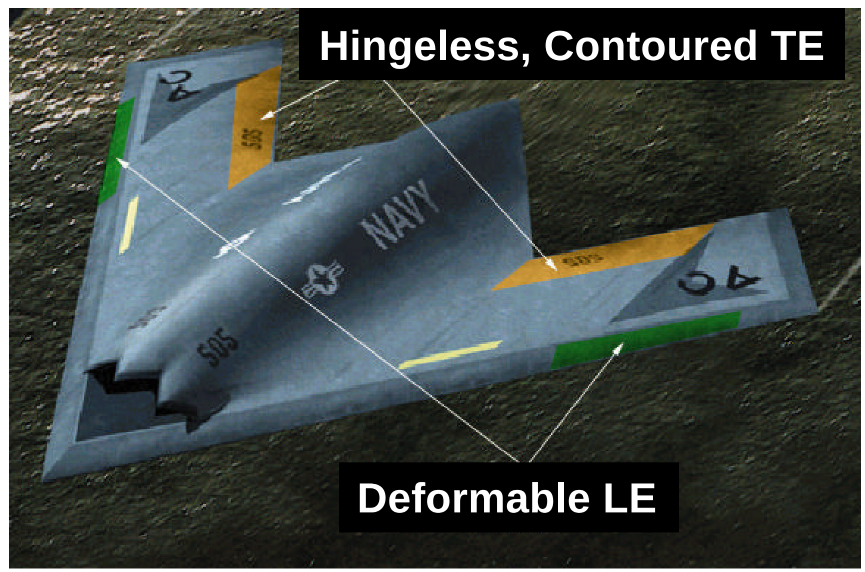
Phase 1



Spanwise Wing Twist using SMA Torque Tube



Contoured Trailing Edge Control Surfaces



Phase 2

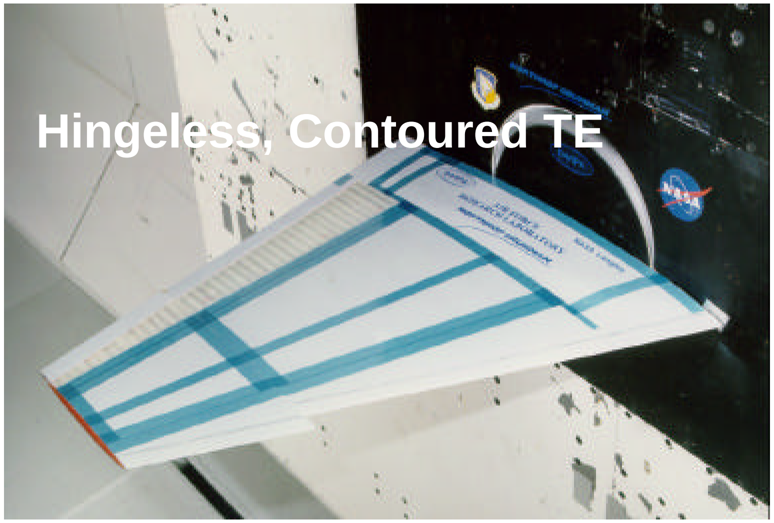
NORTHROP GRUMMAN

Integrated Systems and Aerostructures

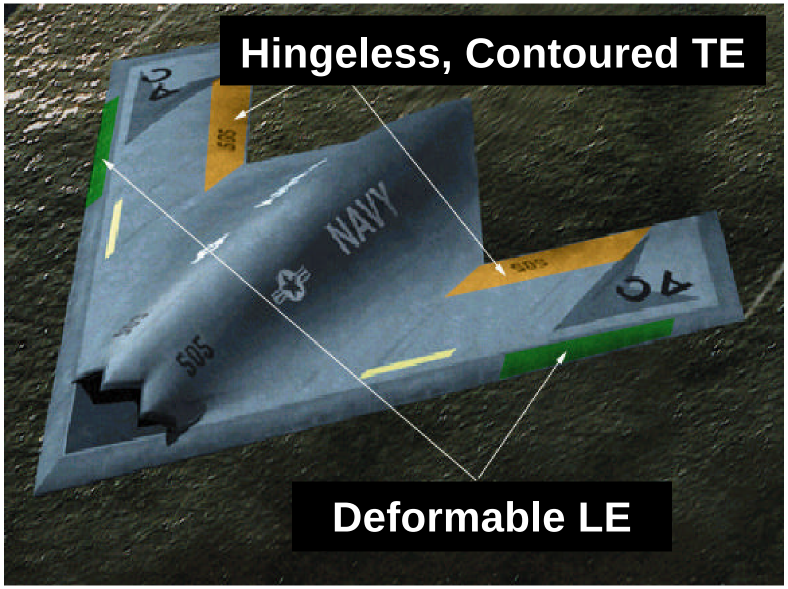
Program Scope

Phase 1(Jan 95-Dec 98)

PHASE 1: 16% Scale Smart and Conventional Wind Tunnel Models of a Fighter a/c Wing Developed and Tested at NASA LaRc; 8 to 12% Improvement in Rolling Moment and Lift Demonstrated for the Smart Wing Design with Hingeless Contoured TE Control Surfaces.



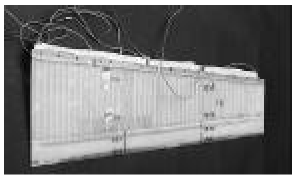
Phase 2 (Jan 97 - April 01)



PHASE 2: 30%Scale Full-span Model of a UCAV design developed and First Wind Tunnel Test Completed. Improvement in Roll Performance Using Chordwise and Spanwise Deformable TE and LE CS Demonstrated. Test 2, With High Bandwidth Actuation System Scheduled for Feb. 01.

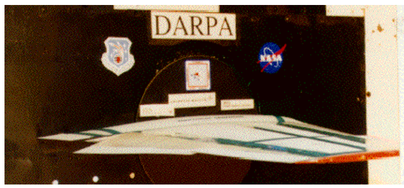
Program Development

Smart Wing Phase 1 Test 1



- Develop Actuators using Smart Materials
- Integrate Actuators into Wind Tunnel Model
- Test Actuator Performance in Wind Tunnel

Smart Wing Phase 1 Test 2



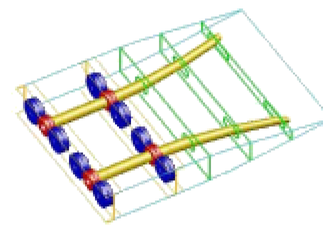
- Improve Actuators (Fatigue Prop., Control, Fab.)
- Using New Balance, Refine Aero Performance Measurements
- Investigate Power Management

1995 - 1998

Smart Wing Phase 2 Test 1

- Develop LE and TE Actuator Systems
- Integrate into UCAV Model
- Test Maneuver Performance at Transonic Speeds (M=0.8)

Smart Wing Phase 2 Test 2



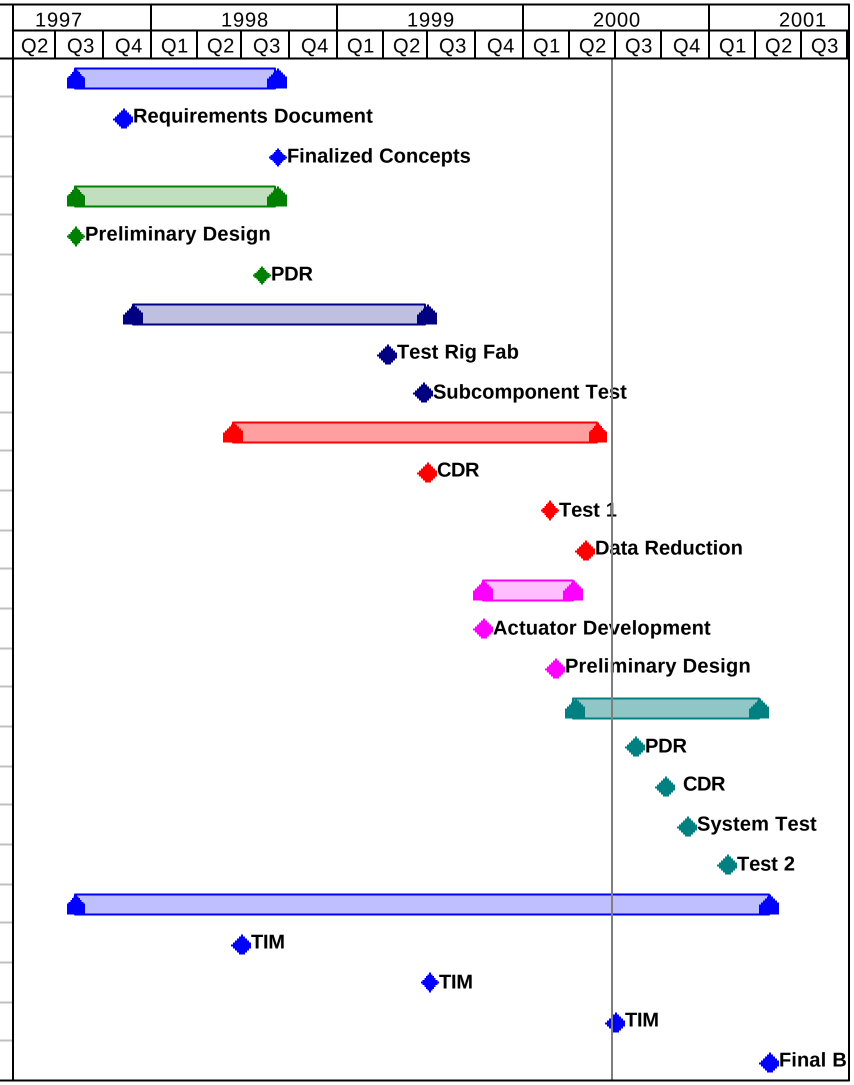
- Develop High Response Actuator System (>10hz)
- Develop Control Laws for Actuator System Testing

1997 - 2001

Smart Wing Phase 3 - Smart Vehicle, UAVs

Phase 2 Schedule

ID	Task Name
1	**Task 1 - Phase 1 Concept Refinements**
2	Requirements Document
3	Finalized Concepts
4	**Task 2 - System Optimization and Analytical Studies**
5	Preliminary Design
6	Preliminary Design Review
7	**Task 3 - Actuation System Development**
8	Test Rig Fab
9	Subcomponent Test
10	**Task 4 - Fabrication and 1st Wind Tunnel Test**
11	Critical Design Review
12	Wind Tunnel Test 1
13	Data Reduction
14	**Task 5 - High Rate Actuator Development**
15	Actuator Concept Development
16	Preliminary Design
17	**Task 6 - 2nd Wind Tunnel Test**
18	Detailed Design / Preliminary Design Review
19	Critical Design Review
20	Actuator System Test
21	Wind Tunnel Test 2
22	**Task 7 - Documentation & Technology Transition**
23	TIM
24	TIM
25	TIM
26	Final Briefing



Program Team

Team Member	Program Role	Status
Northrop Grumman (75%)	Program Lead, System Integration	Test 2 Preparations / System Integration
Lockheed Martin (10%)	SMA Control Surfaces, Control System Analysis	Flex Structure Development
West Engineering (5%)	Control System Development	Initiated Control System for Test 2
Georgia Tech (1.6%)	PZT Pump	Testing Pump, Final Pump Fab for Test 2
Luna Innovations (1.8%)	F/O Sensors	F/O Sensor System for Test 2
Others (UCLA, RSC, SRI, UTA) (6.5%)	Thin Film SMA, PZT Inchworm Motors, EAP Studies, Novel Act. Studies	Work Completed

Govt. Team Member	Program Role	Status
AFRL	Program Monitor, Tech. Transition	Air Vehicle Integration, Follow-on Program Develop.
NASA Langley	Wind Tunnel Testing, Instrumentation, CFD	Preparing for Test 2
Naval Research Lab.	Smart Material Modeling	Work Essentially Complete

Major Accomplishments (June 99 - Present)

- Phase 2, First Wind Tunnel Test Completed
  - SMA Actuated Leading Edge and Trailing Edge Demonstrated
  - SMA Control Surfaces Deflected at Low Transonic Speed (M= 0.8)
  - Improvement in Roll Performance due to Combined Control Surfaces Quantified
  - Control Laws and Power Requirements for SMA Surfaces Developed and Demonstrated
- High Torque Ultrasonic Motor / Actuation System in Development
- Piezoelectric Pump Run at High Rate (~100 Hz)

Program Lessons Learned

Benefits

- Improved Maneuver Performance at the Flight Conditions Tested in Wind Tunnel (Steady State)
- Reduction in the Loss of Aileron Effectiveness

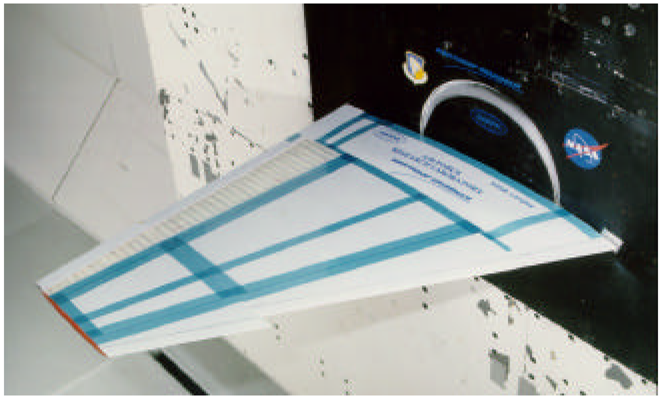
- Other Benefits
  - Integration of Non-Hydraulic Control Surface Actuation System
  - Conformal Control Surface Integration (Reduced Observability)
- Issues and Challenges
  - Smart Materials Selection (Rate / Force Trade-off)
  - Power Systems / Integration with Air Vehicle Power System
  - Flexible Structure Development (Materials, Integration, Redundancy)
  - Increased Control System Requirement (Distributed Actuators, Complex System Variables / Non Linear Behavior)

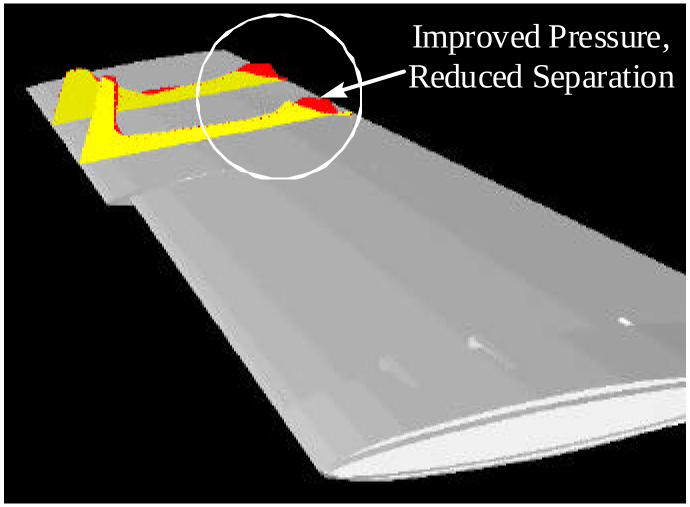
Program Transition

- Current Technology Readiness Level (TRL) is 3 - 5
- Near-Term Application will be for ISR (Intelligence, Surveillance and Reconnaissance) UAVs and Multi-Mission UAVs
  - Potential Customers are Air Force (Global Hawk Upgrades and Sensor Craft) and Navy (Navy UCAV)
- Multi-Mission UAVs would Require Ground-Up, Clean Sheet Design and Integration of Other ‘Smart’ Technologies Such As Conformal Load Bearing Antennas (CLAS)
- Transition to Manned Systems Will Require Significant Development

Program Overview - Phase 1

- Two Tests Completed in NASA Langley Transonic Dynamics Tunnel (TDT)
- Test One - May 1996
  - Demonstrated Trailing Edge Control Surface Actuation with SMA Embedded Wires
  - Wing Twist (Inboard to Outboard) of 1.25° With SMA Torque Tubes
- Test 2 - July 1998
  - Increased Wing Twist to 5°
  - Greater and More Uniform Control Surface Deflection (Up to 15°)





Aileron Pressure Improvement

NORTHROP GRUMMAN

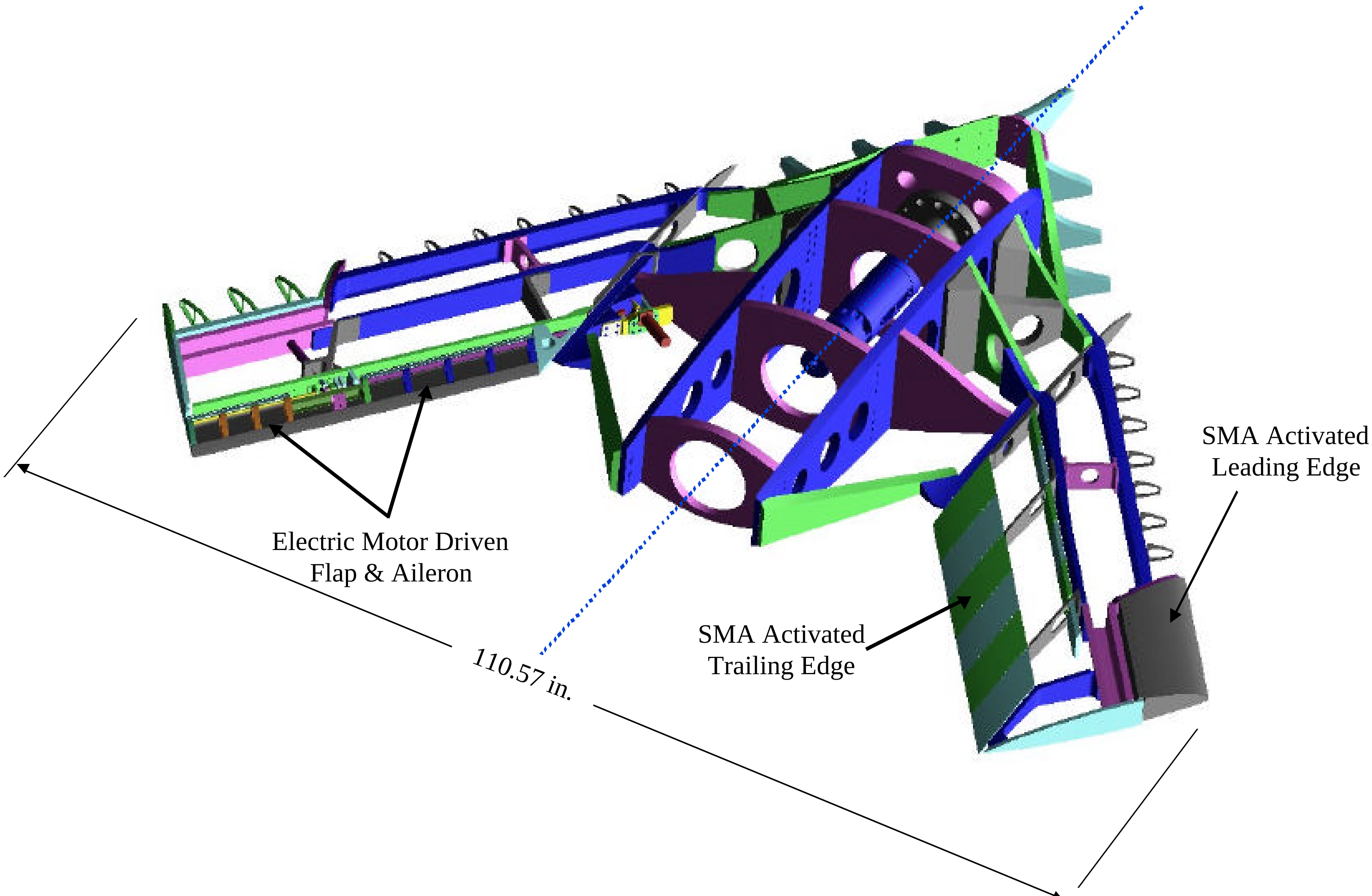
Integrated Systems and Aerostructures

Program Overview - Phase 2

- Objectives
  - Smart Structures Application to Larger-Scale, Higher-Speed Model - Approaches Actual UAV Dimensions
  - More General Smart Structure Application - Leading Edge & Trailing Edge Control Surfaces
  - Increased Actuation Bandwidth
- Features of Selected UCAV Configuration
  - Advanced Tailless Aircraft Configuration
  - Leverages Existing NGC UCAV Design, Database
  - Unmanned Aircraft - Appropriate Risk and Cost Levels
  - Suitable Size, Mission for Smart Structures Demonstration

Test 1 Summary

Wind Tunnel Model - Test 1



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Integrated Systems and Aerostructures

Smart Trailing Edge Spanwise Variation

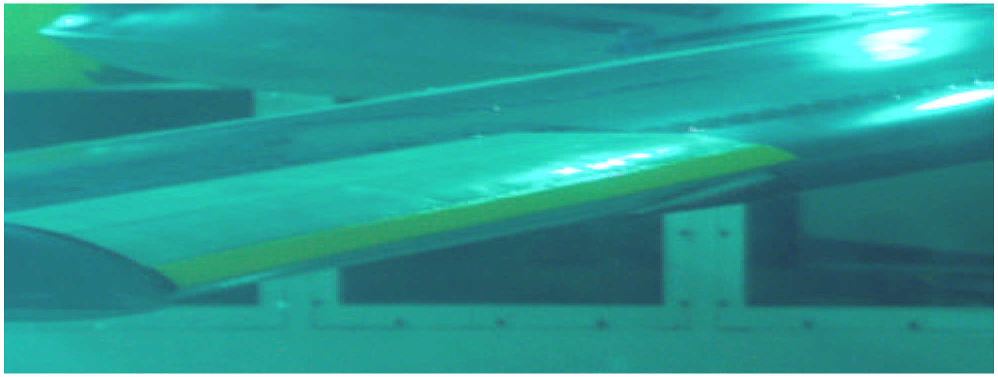
- 6 Spanwise Segments Controlled and Deflected
- Deflection Varies from 0° Inboard to 6°

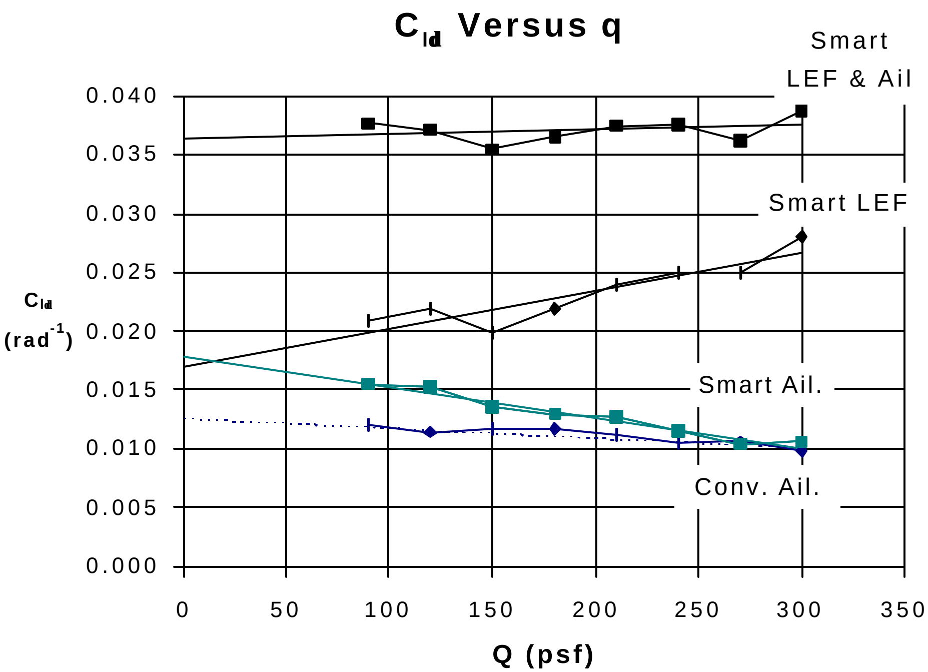
Test Operation Summary

- Test Run in Three Groups
  - Mach = 0.25 **Air** (Dynamic Pressure 90 PSF)
  - Mach = 0.6 and 0.8 **Heavy Gas** (Dynamic Pressure 180 PSF to 300 PSF)
- Data Recorded at Fixed Angles of Attack from -6° to a Maximum of +15° (Range Dependent on Conditions)
- Model Configurations Tested
  - Conventional
    - Aileron Only (±15°), Elevon Only, (±15°), Both Deflected (±15°)
  - Smart
    - Aileron Only (±8°), Trailing Edge Spanwise Variation Inboard to Outboard
    - Leading Edge Deflection (-4.5°) w/ Aileron Deflected

Aeroelastic Effects of LE Flap and Aileron

- Rigid (q=0) LEF, Aileron Effectiveness Comparable
- LEF Effectiveness Amplified, Aileron Reduced With Increased q
- Combined LEF, Aileron Allows Minimum Deflection For a Given Roll Rate





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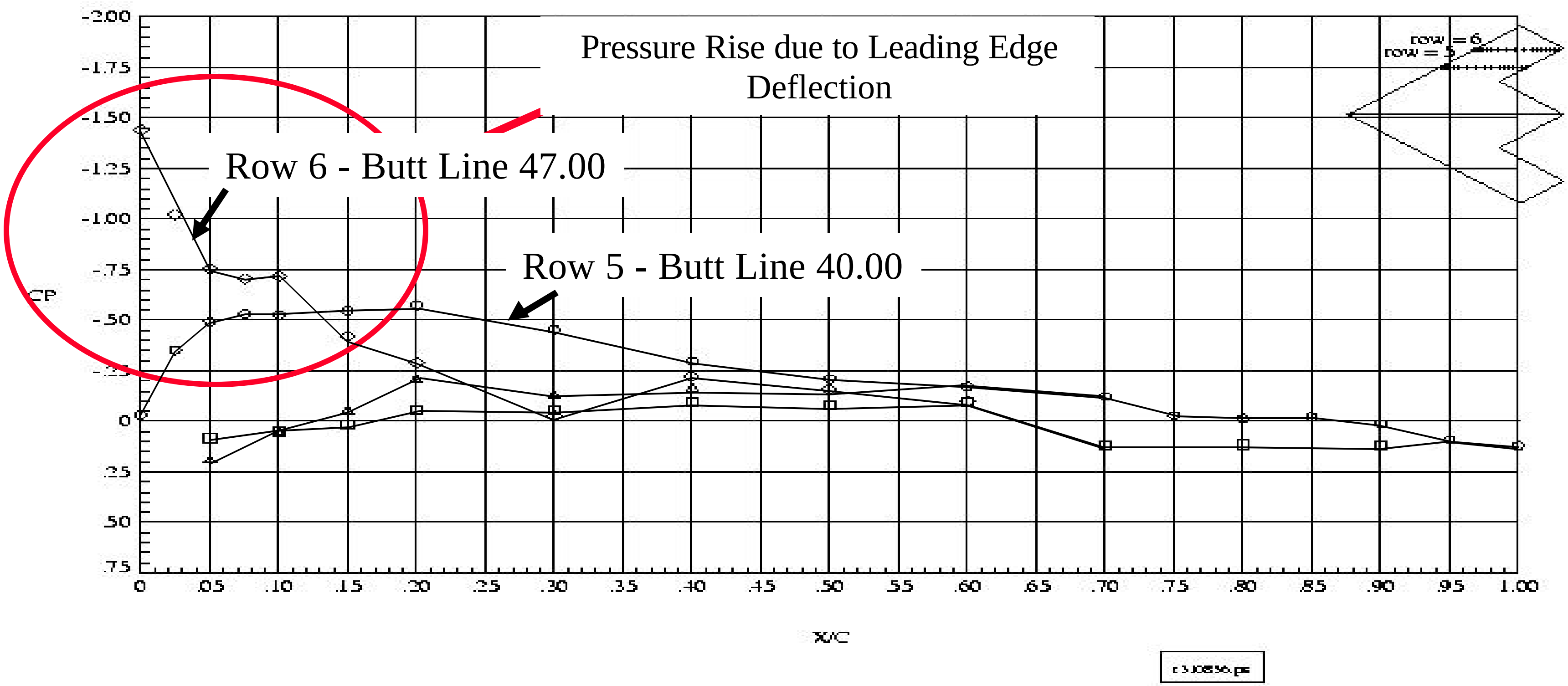
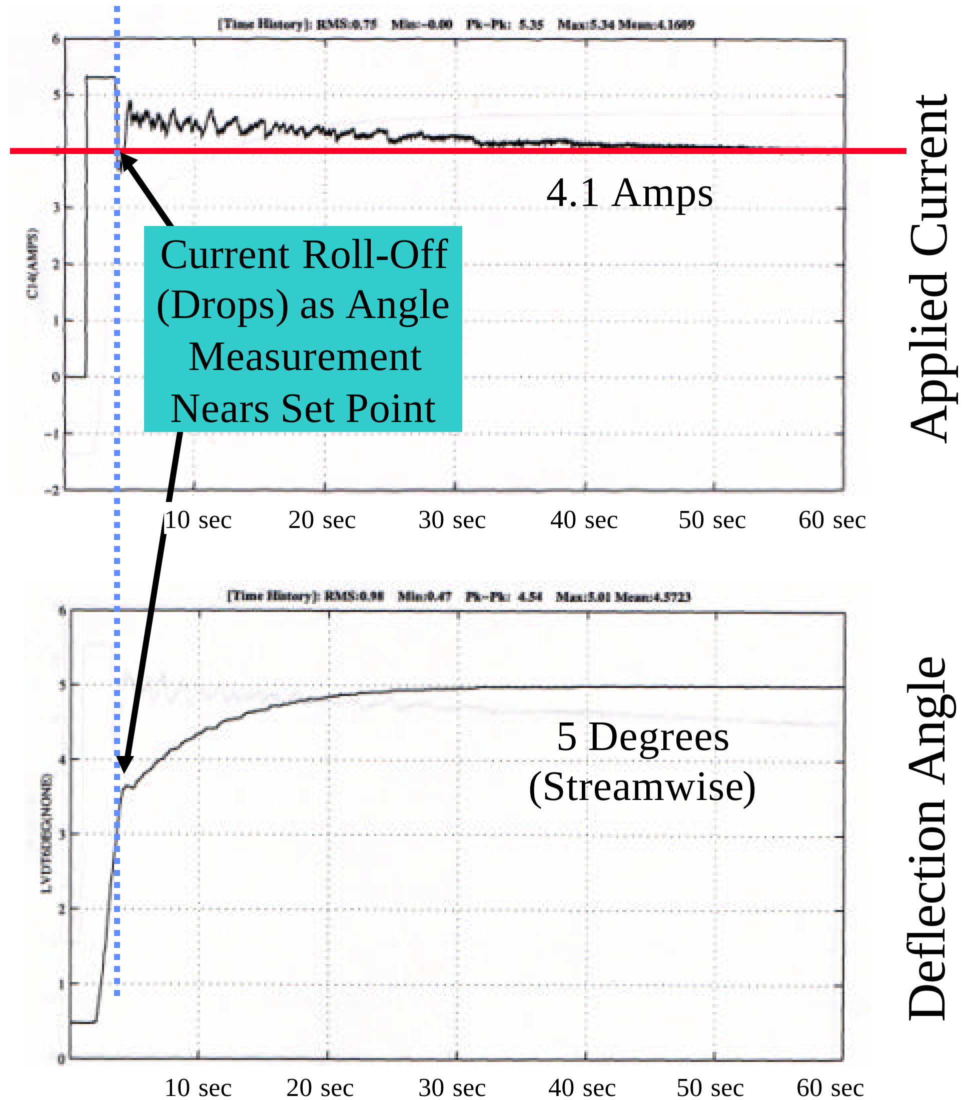
Smart Wing Pressure Data



- Smart LE Deflection Yields Desired Leading Edge Pressure Increase Without Inducing Separation
- Forward Pressure Center Gives Beneficial Aeroelastic Performance

Power and Control

- PID Control Algorithm Able to Control SMA Control Surfaces
- Sustained Deflection Power ~ 210 watts
- Maximum Sustaining Power is a Function of Dynamic Pressure, Deflection Angle and Angle of Attack



Test Summary

- Successful High-Speed Demonstration of SMA Control Surfaces (Mach 0.8, q=300 psf)
- Successful Application of SMA to Highly-Loaded LE Structure
- Meaningful Demonstration LE, TE Aeroelastic Effects on Roll Derivative - Not Feasible From LO Standpoint With Conventional Surfaces
- Accurate, Stable Smart Structure Position Control Under Varying Flight Load Conditions

Test Lessons Learned

- SMA Wire Heating in Internal Cavities May Necessitate Forced Convective Cooling
- Integral Design of SMA Actuation, Control Surface Structure Is Important
- Streamwise Control Surface Segments Significantly Increased Actuator Force Requirements

Test 2 Preparation and Plans

Test 2 Plan

Configuration	Test Goal	Variables
Baseline	**Repeatability**	**Clean**
Combined Elevon / Aileron **(Smart Side Only)**	**Bandwidth Demonstration** **Pitch and Roll Control**	$\dot{d}_{t.e.}$ = 1^{o} to 50^{o} /sec $d_{t.e.}$ = $\pm$ 25^{o}
Non-Uniform Trailing Edge Deflection **(Smart Side Only)**	**Shaping Demonstration** **Pitch and Yaw Control**	**Variation Inboard to Outboard** d_{te} = +25^{o} to -25^{o}
Aileron (Piezo Actuated) **(Conventional Side)**	**Demonstration Piezo Pump Performance and Speed**	$d_{ail.}$ = $\pm$ 25^{o}

Test 2 Test Conditions

	Mach No	Alpha Range	Air or Heavy Gas	Dynamic Pressure
Group 1	0.25	-6° to 16°	Air	90 PSF
Group 2	0.6	-4° to 8°	Heavy Gas	180 PSF 90 to 300 PSF
Group 3	0.8	-4° to 8°	Heavy Gas	180 PSF 90 to 300 PSF

*Flutter Clearance Runs Will Be Done Before Each Group

Actuation System Development

Actuators

Piezo-Hydraulic Actuator

Ultrasonic Motors

Electrostrictive Polymer
Stack Actuators

Transmission

Eccentuators

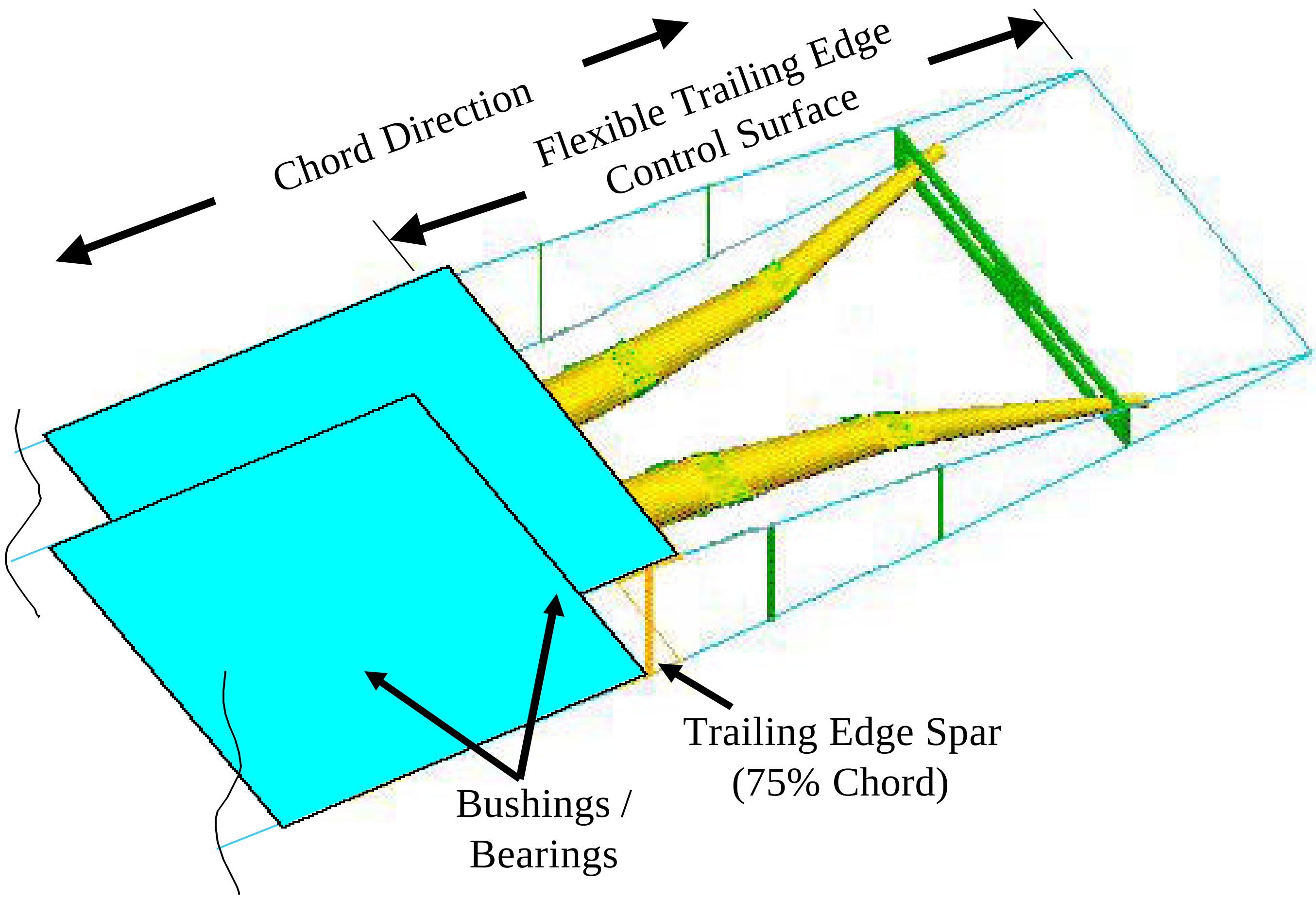
Distributed Forces

Trim Tabs

Development Needs

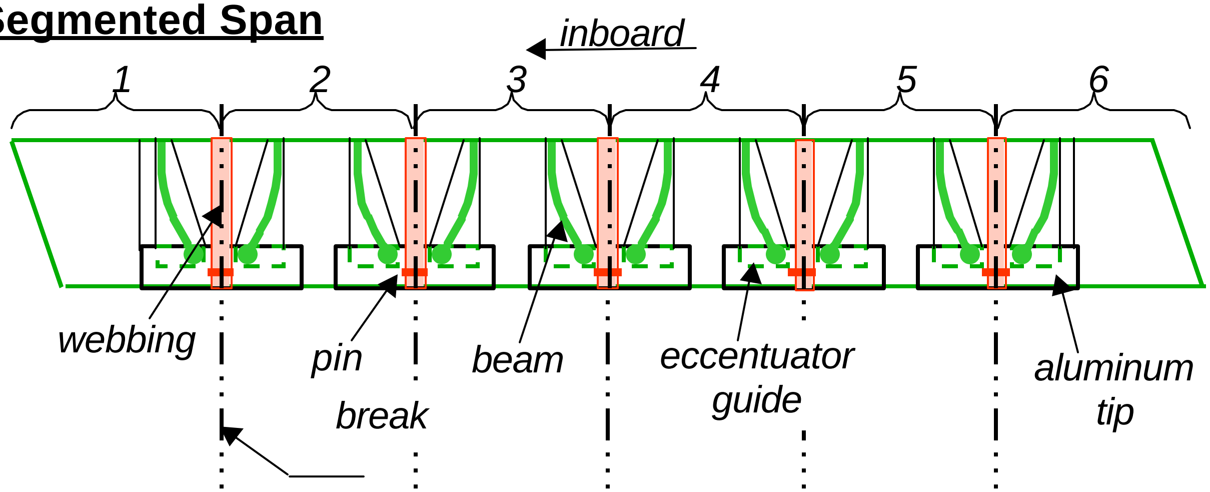
Flexible Structures
Power Supplies
Electrostrictive Polymer Stacks

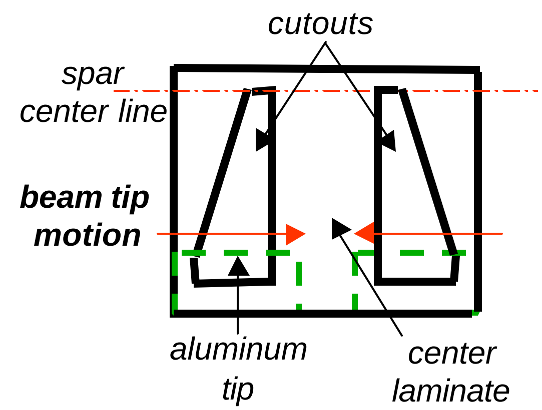
Eccentuator Configuration



Eccentuator Spanwise Configuration

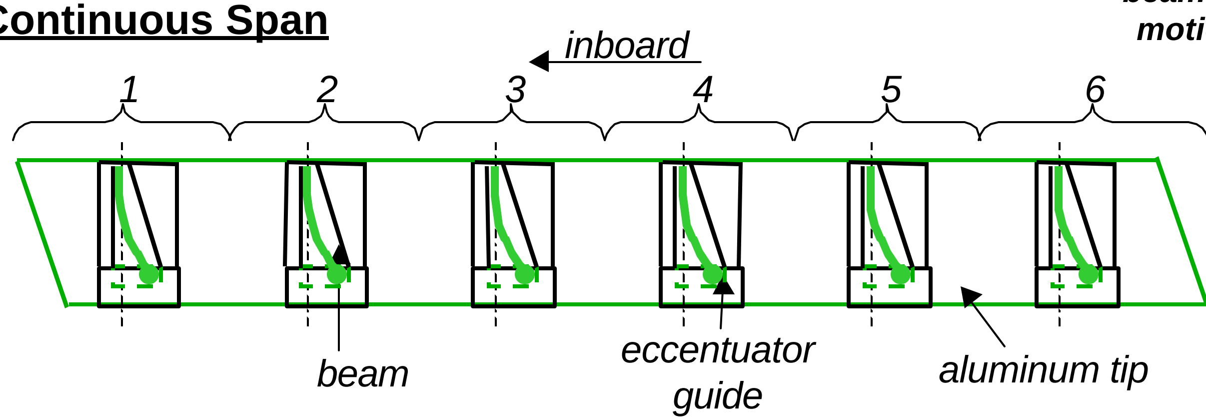
Segmented Span

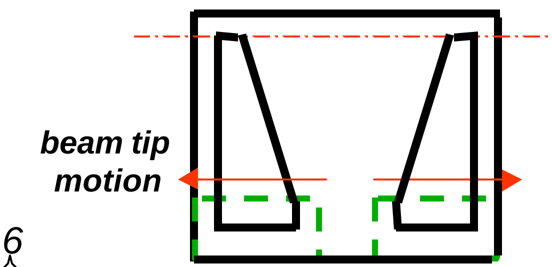




Configuration 1

Continuous Span

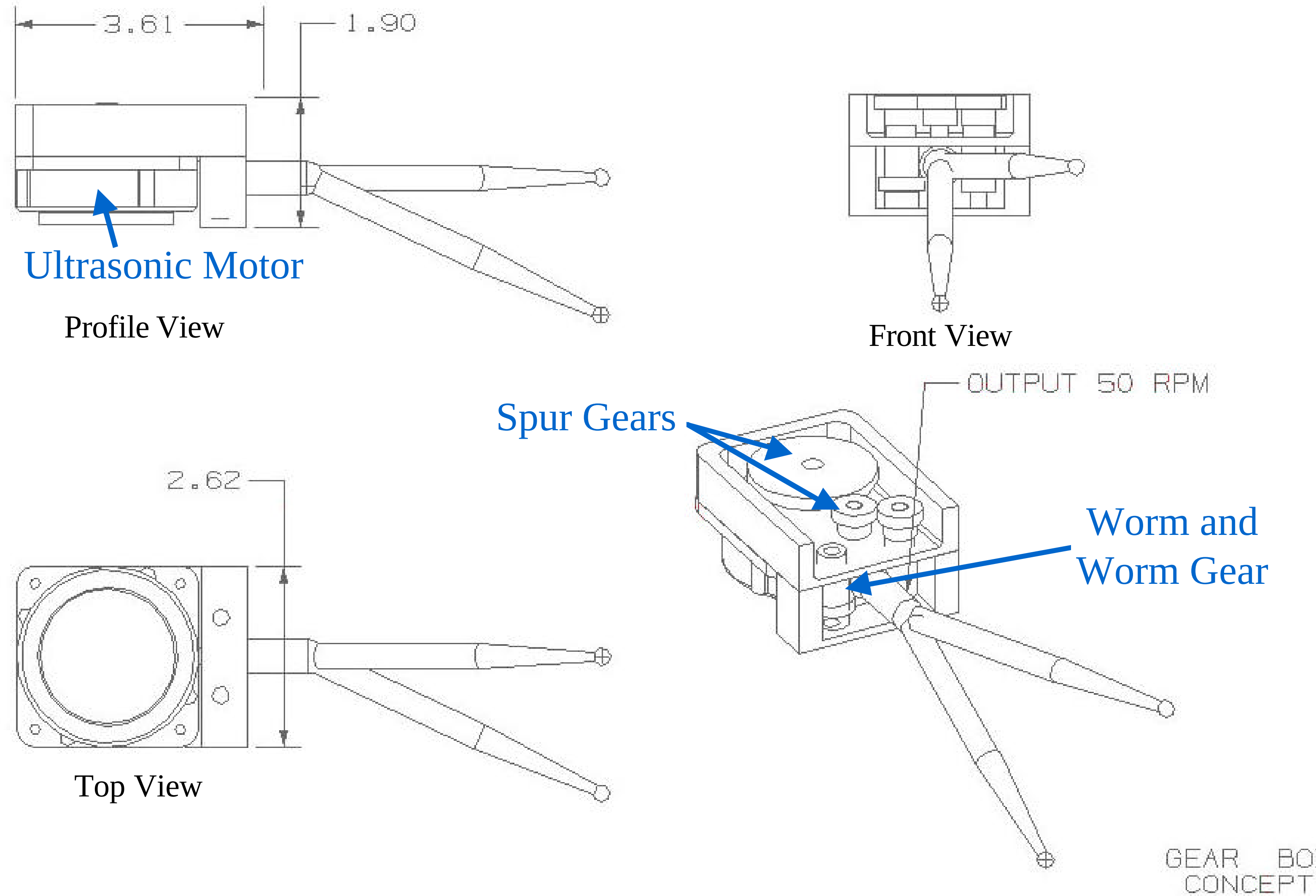




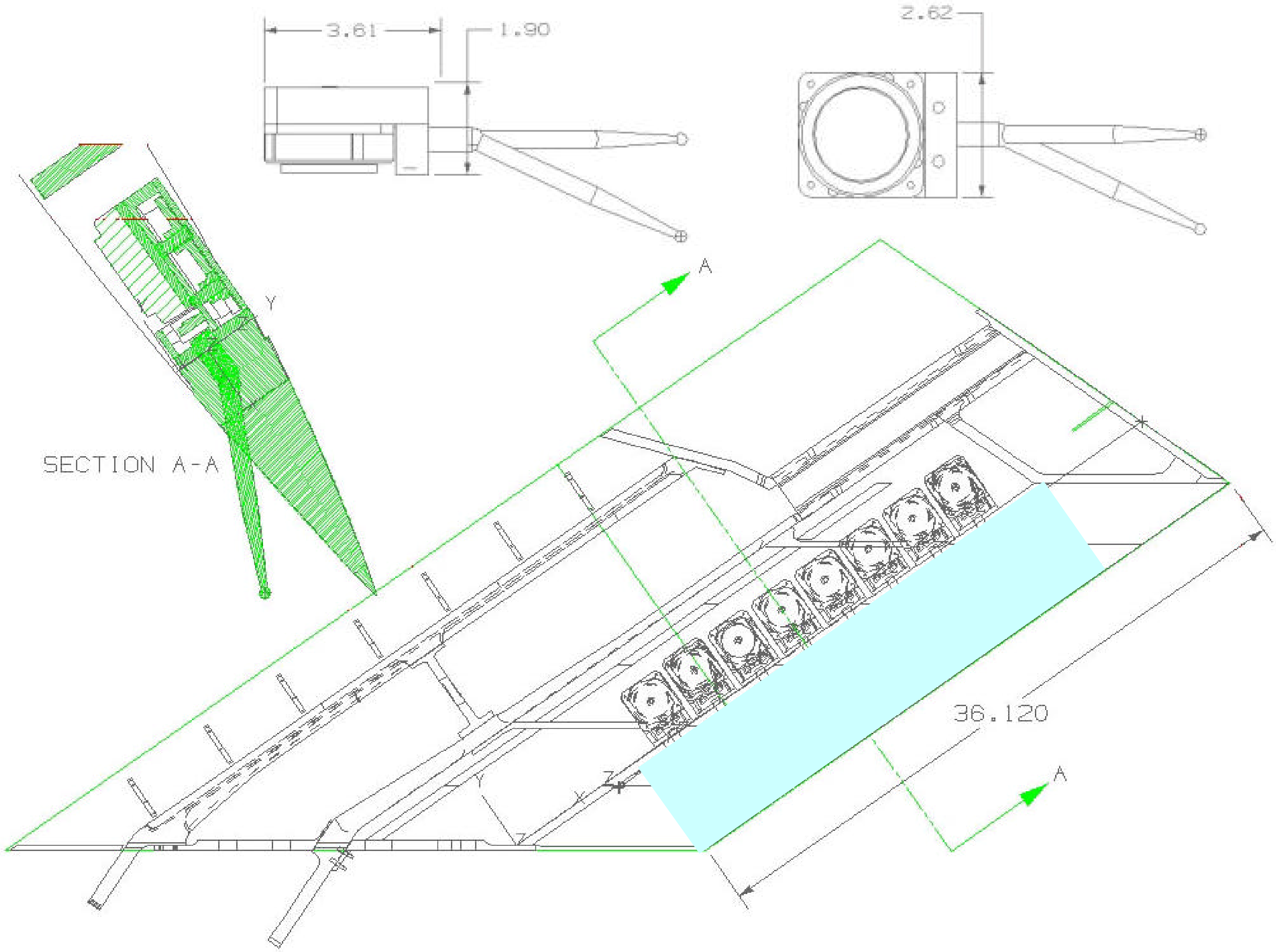
Configuration 2

Integrated Systems and Aerostructures

Ultrasonic Motor and Gearbox



Planview with Installed Motor & Gearboxes



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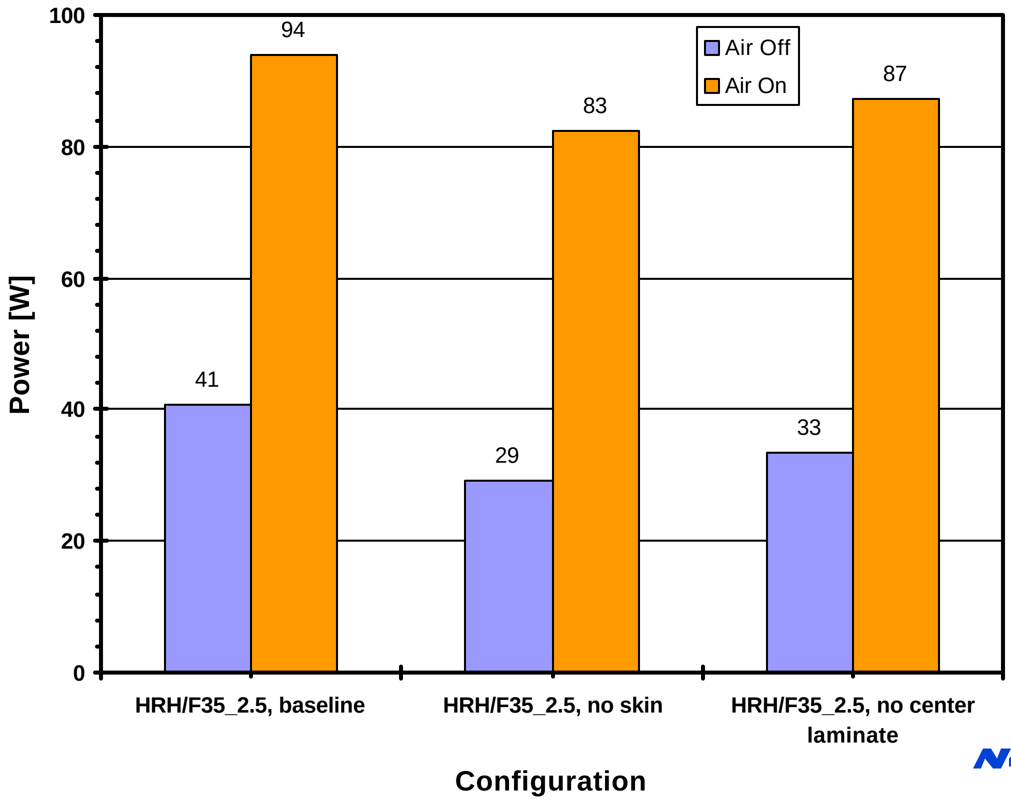
Integrated Systems and Aerostructures

Skin & Center Laminate Stiffness Contribution

Actuation Power Vs. Skin & Center Laminate

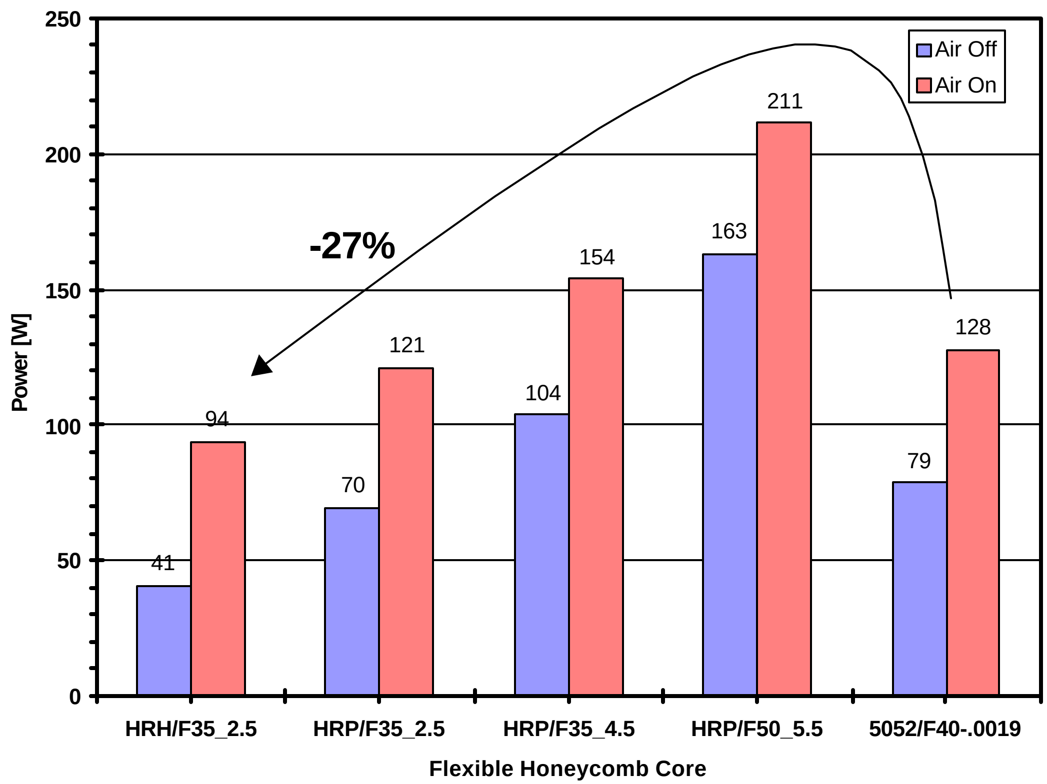
	Air Off		Air On	
Configuration	**Power [W]**	**% baseline**	**Power [W]**	**% baseline**
HRH/F35_2.5, baseline	40.7	N/A	93.9	N/A
HRH/F35_2.5, no skin	29.2	72%	82.5	88%
HRH/F35_2.5, no center laminate	33.3	82%	87.2	93%

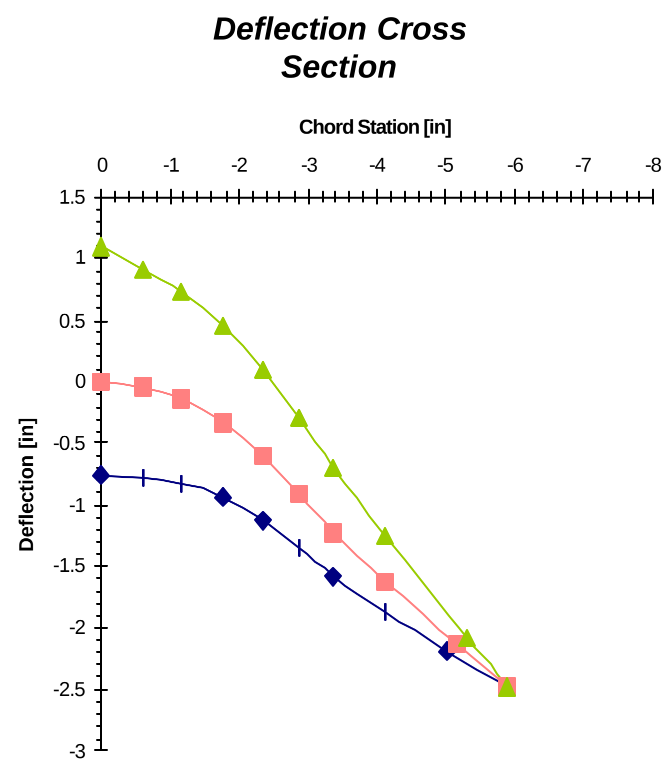


Core Stiffness Influence

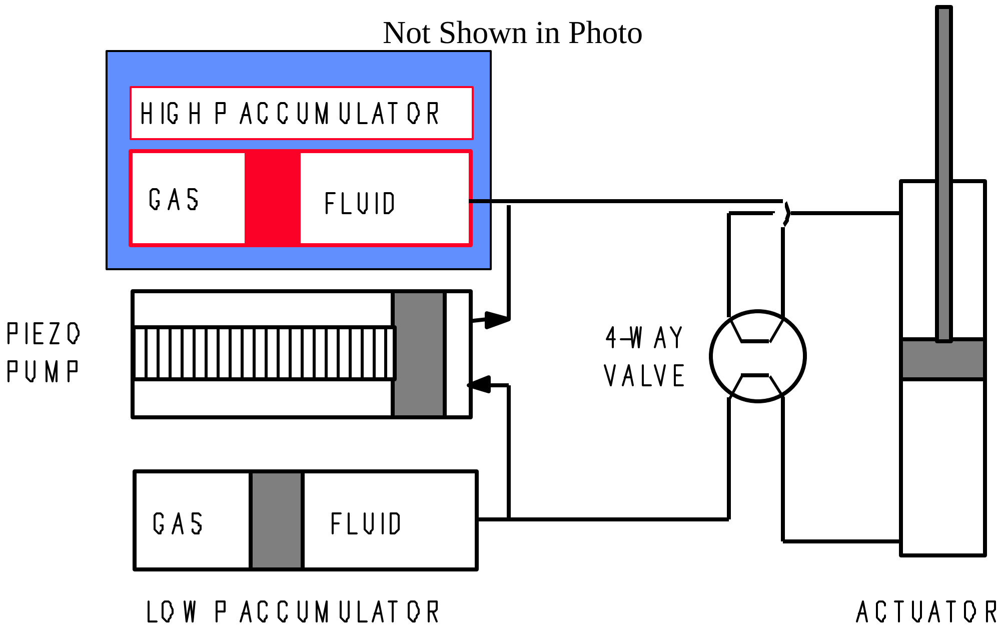
Actuation Power Vs. Core Type

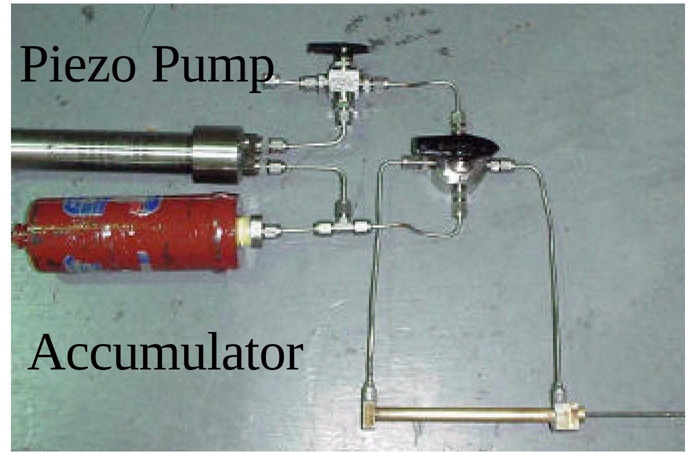
Core	Ezz [ksi]	GL [ksi]	GW [ksi]	Power [W] Air Off	Air On	% Structure
HRH/F35_2.5	12	4	2.5	40.7	93.9	43%
HRP/F35_2.5	25	12	7	69.6	121.0	58%
HRP/F35_4.5	49	22	12	104.0	153.9	68%
HRP/F50_5.5	61	40	18	163.3	211.4	77%
5052/F40-.0019	125	32	13	78.6	127.6	62%

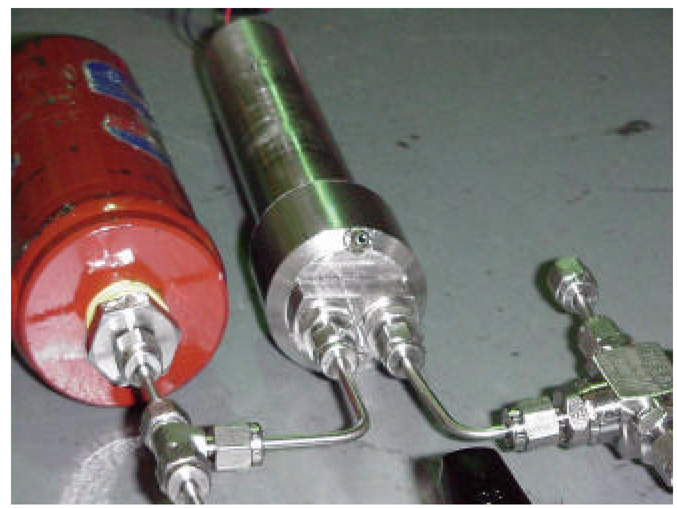




Piezoceramic Actuated Pump







Pump with low pressure accumulator and actuator

- Performance
  - 0.5 inch per second
  - 120 pound blocking force
  - Recently Operated at ~100 Hz with High Current Power Supply and No High Pressure Accumulator

Summary Remarks

Program Lessons Learned

Benefits

- Improved Maneuver Performance at the Flight Conditions Tested in Wind Tunnel (Steady State)
- Reduction in the Loss of Aileron Effectiveness

- Other Benefits
  - Integration of Non-Hydraulic Control Surface Actuation System
  - Conformal Control Surface Integration (Reduced Observability)
- Issues and Challenges
  - Smart Materials Selection (Rate / Force Trade-off)
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Program Transition

- Current Technology Readiness Level (TRL) is 3 - 5
- Near-Term Application will be for ISR (Intelligence, Surveillance and Reconnaissance) UAVs and Multi-Mission UAVs
  - Potential Customers are Air Force (Global Hawk Upgrades and Sensor Craft) and Navy (Navy UCAV)
- Multi-Mission UAVs would Require Ground-Up, Clean Sheet Design and Integration of Other ‘Smart’ Technologies Such As Conformal Load Bearing Antennas (CLAS)
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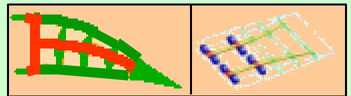
Smart Wing Technology Transition

Piezoelectrics

Technology Applications:
Flutter Suppression, Buffet Load Alleviation



Eccentuator
Electrostrictive Polymers
Ultrasonic Motors

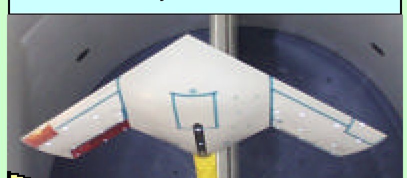
Technology Applications:
Universal Usage for Commercial, Fighters, UAVs, etc.

Smart Wing Phase II Development

Rate Capability

Shape Memory Alloys

Technology Applications:
Low-Bandwidth Actuation, Active Inlet Geometry Modification



Displacement Capability

Smart Actuation Development

Technology Transition, Maturation

NORTHROP GRUMMAN
Integrated Systems and Aerostructures

Smart Wing II
Program Review

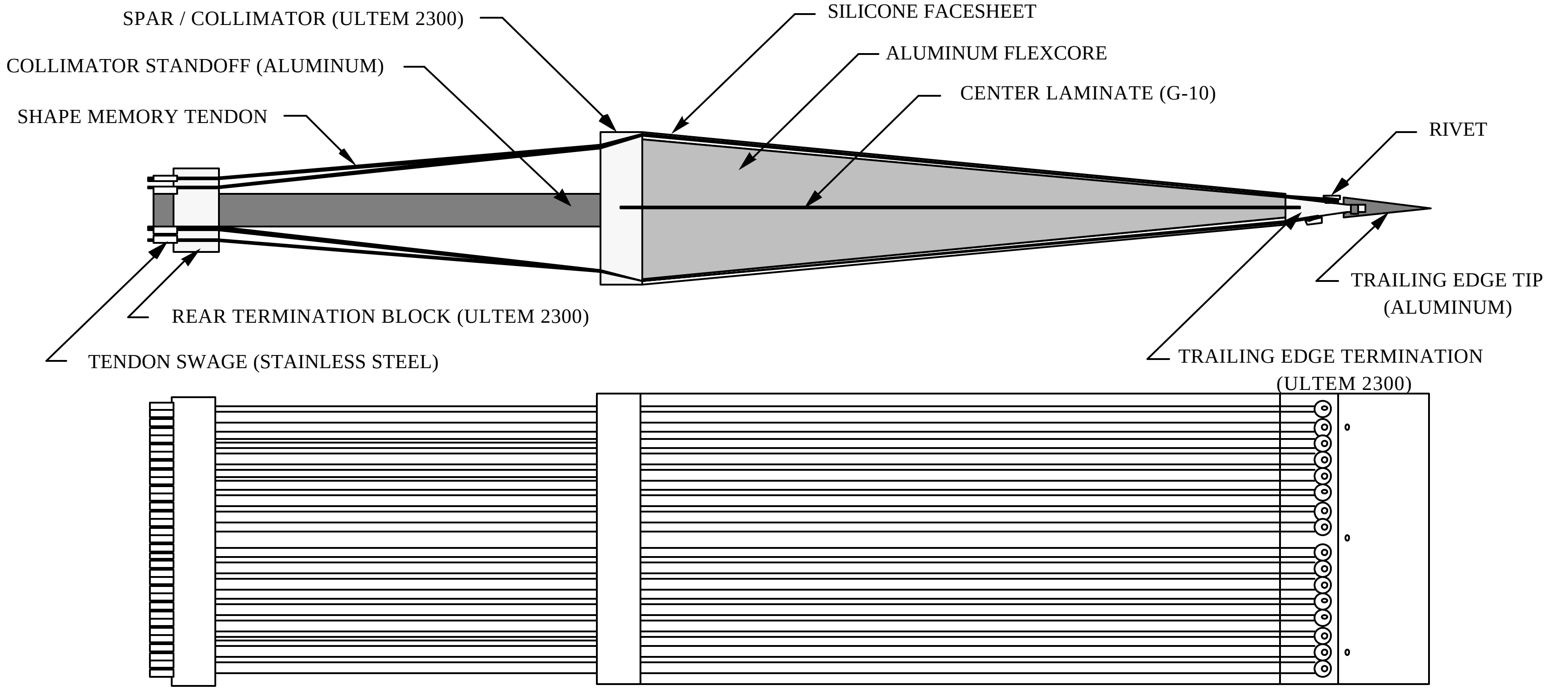
June 26, 2000

Bernie Carpenter

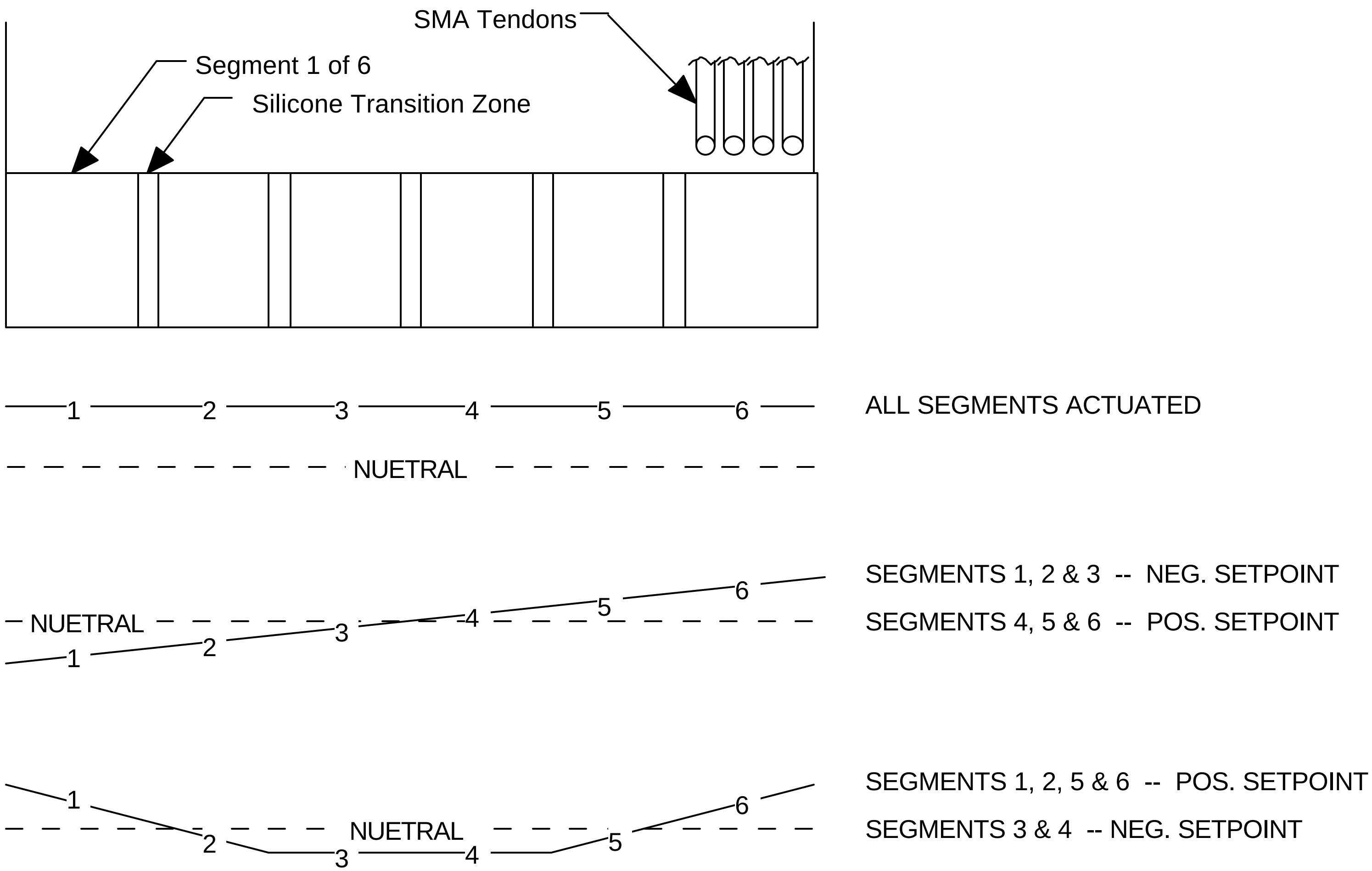
Lockheed Martin Astronautics

LOCKHEED MARTIN

Trailing Edge Demonstration Article



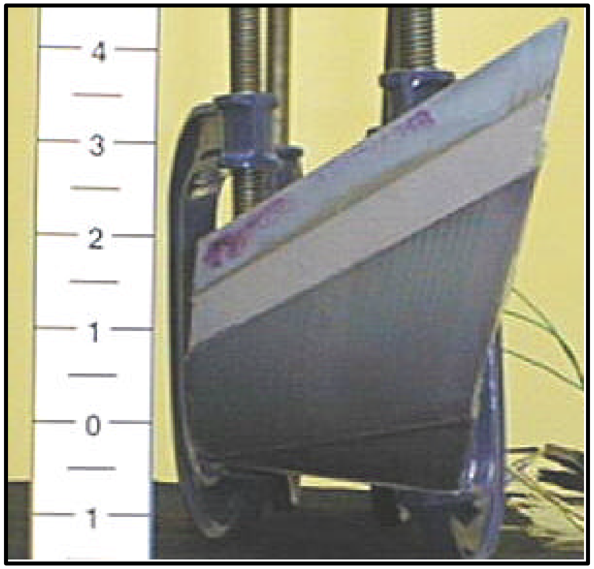
Semi-Rigid Trailing Edge

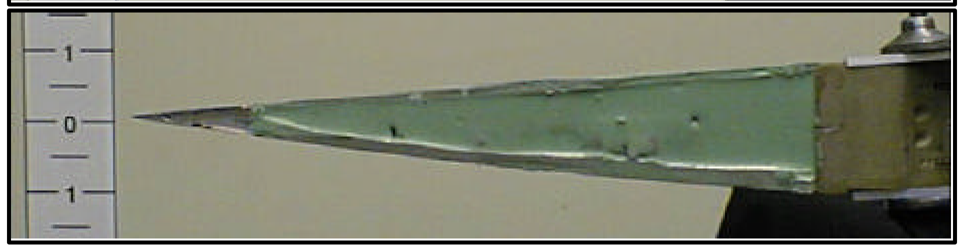


LOCKHEED MARTIN

Deflection Capability of Independent SMA Segment

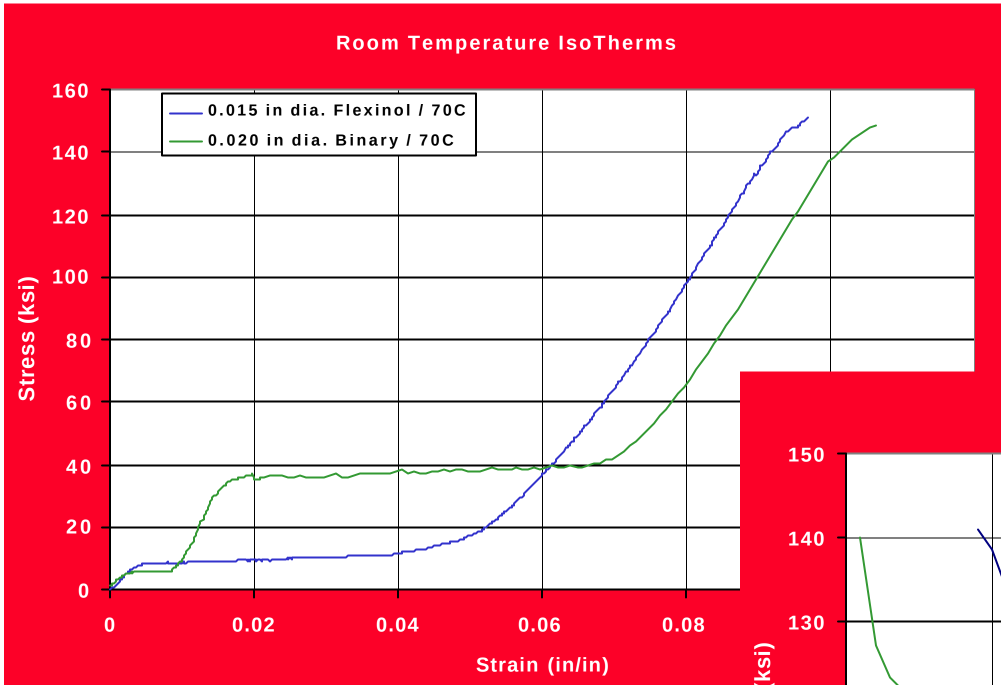
- Inboard Deflection 1/2 of Outboard Deflection

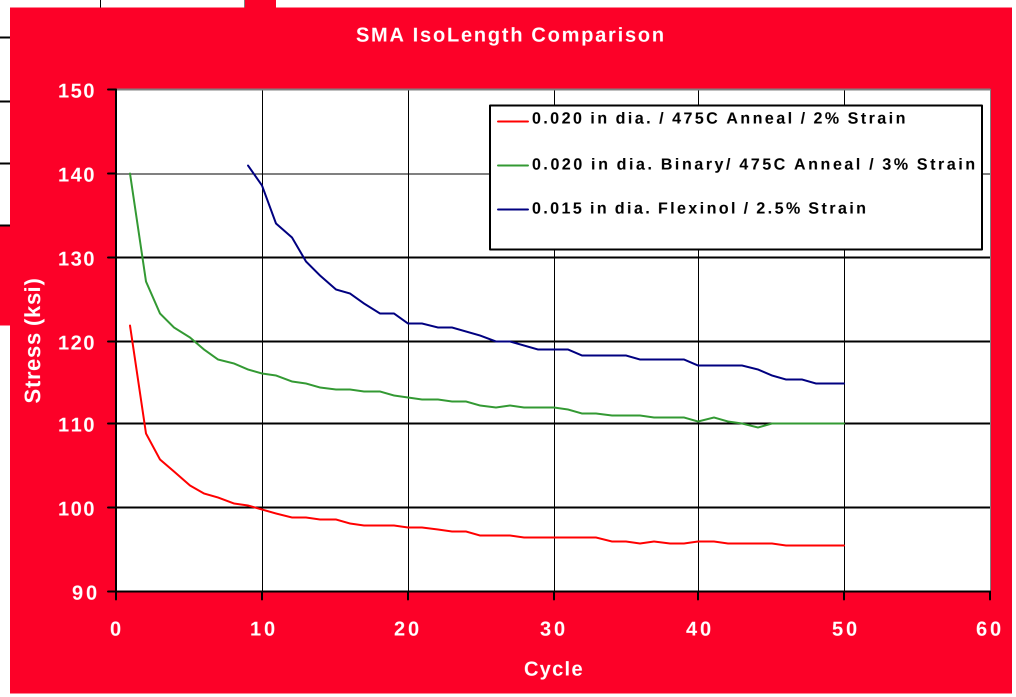




LOCKHEED MARTIN

Shape Memory Wire Comparison





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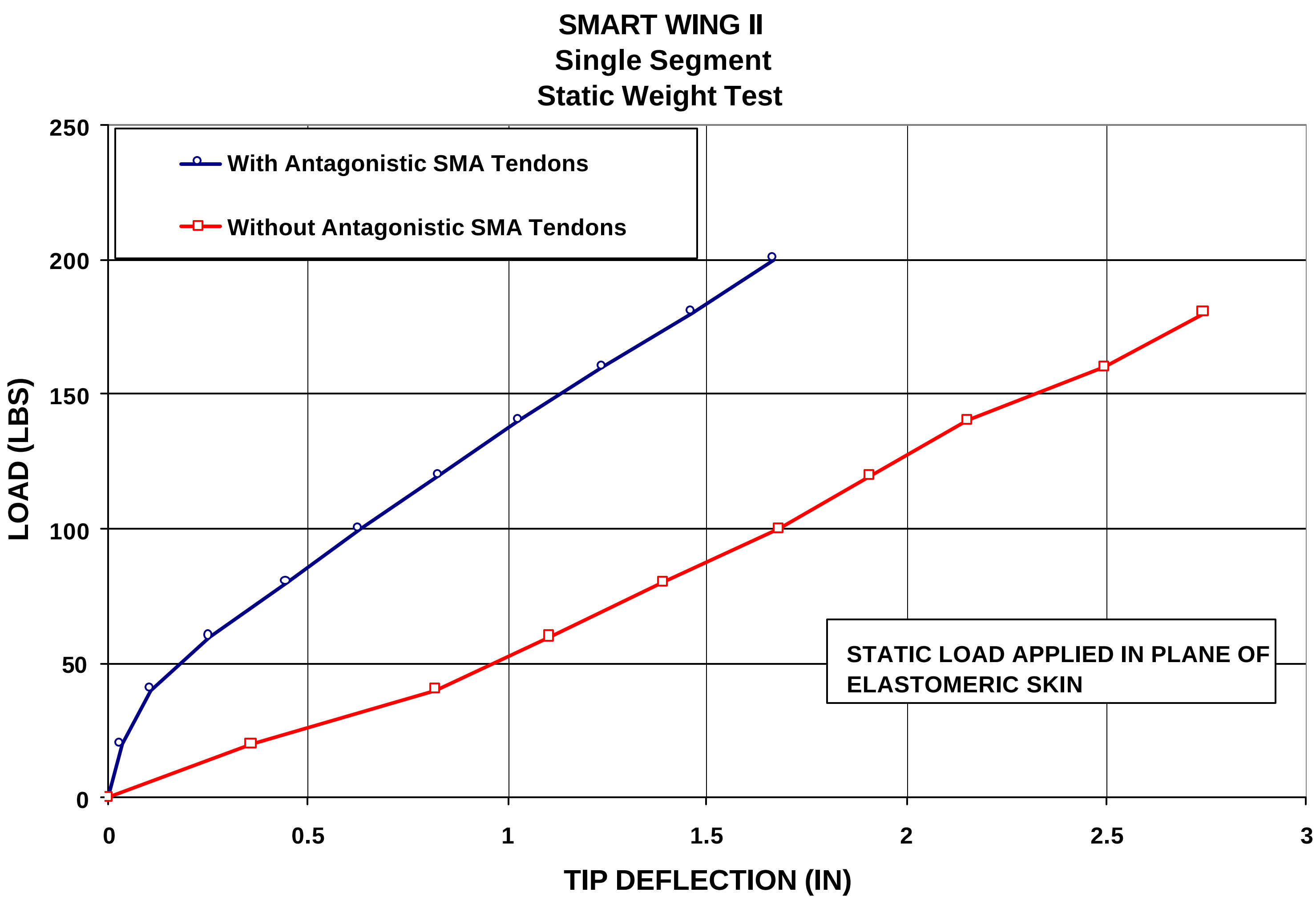
Swept Segment Static Weight Test



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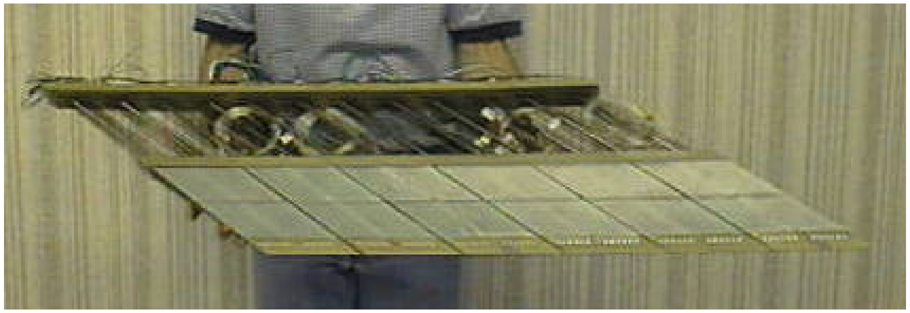
Structural Stiffness

- Center Laminate Provides Support for termination blocks
- Flexcore™ Defines Control Surface Shape
- Elastomeric Skins Create “Smooth” Surface and Retains Wires
- Deflection Controlled by Wire Length, Stiffness and Apparent Hinge Line
- Leading Edge

- Trailing Edge



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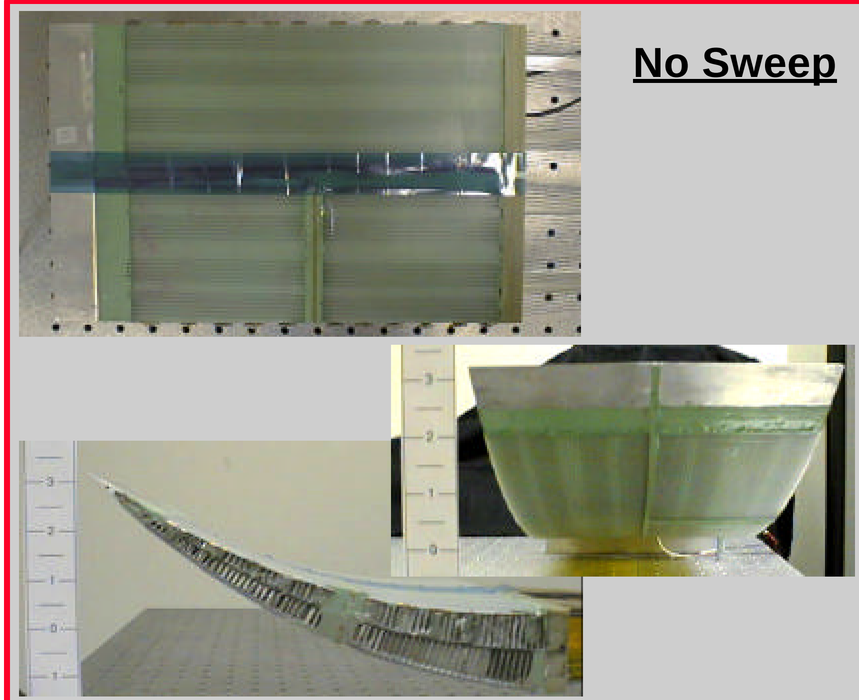
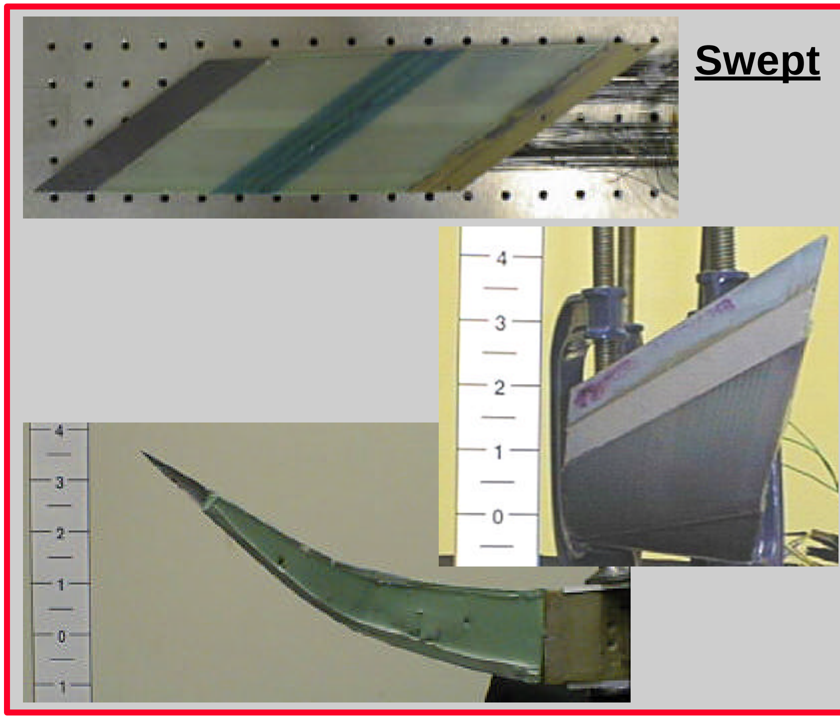
Effect of Sweep Angle

- Configurations





- Control System Authority
  - Wires per segment = 24
  - Total Force (six segments) > 2000 lbs
  - Force to deform:
    - Swept ≈ 1400

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System Integration

- Verified Control System Capability
- Verified Deflection
- Verified Assembly and Joining Methods
- Full System Assembly Done at LaRC
  - Linking of SMA segments
  - Control system testing with all LVDTs
  - Connection to programmable power supplies
- Observations
  - Inability to meet system deflection requirements resulted in SMA wire degradation
    - Sweep angle introduces compliance issues through pinned joints
    - Reach SMA force boundary before displacement boundary
  - Control System Based on Displacement Feedback
    - Current limits employed but set high to get bandwidth
      - Used to limit short circuit
    - Integration continues to supply current driving SMA temperature beyond maximum use

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Results

- Span Control
  - Demonstrated but at Low Deflection
- Structural Stiffness Critical Design Element
  - Need Compliant Structure
  - Vary Structural Stiffness
  - Sufficient Actuation Authority
- System Integration Critical
  - System Complexity and Costs Increasing
  - Despite Modular Approach, In-Field Repair Difficult
  - Full-Up Tests with Schedule Tolerance
- Bandwidth Limitations
  - Structurally Integrated Hybrid
  - Traditional Mechanical Design Alternative
    - Verification of performance using compliant structure

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